SMOKE COLUMN HEIGHT RELATED TO FIRE INTENSITY

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ABSTRACT

Height of slash fire smoke columns, commonly thought to be a function of atmospheric conditions alone, through a series of 10-acre experimental fires is shown to be strongly related to fire intensity. By conducting intense fires, land managers can possibly burn forest debris and still maintain air quality when atmospheric conditions are less than ideal for smoke dispersal.

OXFORD: 332.3: 436. KEYWORDS: slash disposal, fire use, atmospheric conditions.

INTRODUCTION

Disposing of logging debris grows increasingly difficult because of the constraints, demands, and restrictions being imposed on how it may be done. A growing public concern for air quality is one of the most important constraints on slash burning. Oftentimes land managers have given too little attention to proper smoke dispersal. The public, rightly so, will no longer tolerate degradation of the air. Land managers must assume the responsibility for burning slash in a way that maintains air quality.

Proper scheduling of fires in a given locality can avert the all too frequent occurrence of many fires, all burning at once, taxing the atmosphere's smoke dispersal capabilities. However, this alone does not relieve the need to conduct each fire to achieve the best possible smoke control.

The movement of smoke may be divided into two problem areas: (1) controlling the rise of smoke to its ultimate height, and (2) processes that disperse smoke at or near the maximum height. This paper addresses the problem of achieving good smoke elevation.

In the Northwest, prescribed burning is usually done in fall, when fuels are often quite moist and the atmosphere is frequently stable. Burning slash under such conditions results in low-intensity, smoky fires at a time when the atmosphere is least able to disperse the smoke.

Properly done, prescribed fires are aimed at specified objectives and for times and conditions most likely to achieve those objectives. This is true, not only for the purposes of hazard reduction and site preparation, but also for meeting the demands for acceptable elevation of the smoke.

Smoke that reaches a high altitude tends to stay at that altitude until completely dispersed. However, natural forces can also keep smoke near the ground if the fire and the atmosphere do not elevate the smoke initially. The result is then local, ground-level air pollution.

FACTORS AFFECTING SMOKE COLUMN HEIGHT

Because the vertical movement of smoke is dependent upon the temperature difference between the smoke and the surrounding air, much information on smoke movement has come from meteorological studies. The literature abounds with information on the influence of lapse rates on the rise and dispersal of smoke plumes. This is so universally true that, in the minds of many, characteristics of the heat source are of no consequence.

Does heat source influence smoke dispersal? Will a large, high-energy source produce a higher smoke column than a low-energy source under a given lapse rate or, in land managers' terms, will a hot slash fire give better smoke rise than a cool one? The answer to this basic question can have an important bearing on prescribed burning. If fire intensity does indeed influence smoke dispersal, the land manager may find himself less constrained by atmospheric conditions and with a greater flexibility to burn and still meet smoke management objectives.

FIRE INTENSITY

Fire intensity, the rate of heat released from a given fire, is commonly called the unit area energy release rate (Btu/ft^2/min). High fire intensity is achieved only through rapid consumption of large amounts of fuel. Rate of fuel consumption is mainly controlled by fuel moisture, but is also influenced by factors that affect rate of spread, such as wind velocity and steepness of slope. If fire intensity is an important factor in determining ultimate column height, variables that influence fire intensity should also be positively related to the height of smoke rise.

ATMOSPHERIC STABILITY

Atmospheric stability, the rate at which air temperature decreases with an increase in altitude above the surface of the earth, has some well-known effects of smoke rise. Unstable air rapidly decreases in temperature with an increase in altitude. Stable air decreases in temperature much less rapidly with an increase in altitude. *Very* stable air may even increase in temperature with an increase in altitude, resulting in the phenomenon called an inversion. Stable conditions tend to limit smoke rise and keep drift smoke near the ground. Unstable air, on the other hand, will assist smoke rise and help keep surface air clear. Mixing depth is a commonly used measure of atmospheric stability. Mixing depth is *not* always a good prediction of how high the smoke will go and should not be used or considered as such. The mixing depth is only an indication of boundary layer atmospheric stability.

METHODS

Recent experimental slash burning has yielded information that may help tie together some of the previous discussion. Forty-one instrumented fires, each 10 acres in size, were conducted by Flathead National Forest personnel for the Northern Forest Fire Laboratory over a period of 2 years.[1] The location was the Miller Creek Drainage on the Tally Lake Ranger District of the Flathead National Forest, Flathead County, Montana. The fires were broadcast burns of 10-acre beds of continuous slash created when a mature larch-fir stand was commercially clearcut. All residual stems were felled, and all slash was 1 or 2 years old when burned. Twenty-two of these fires were adequately documented to afford a data base for the study of smoke movement.

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[1] Steering Committee. Cooperative studies of the use of fire in silviculture. Prog. Rep. 4, 1970. On file at the Northern Forest Fire Laboratory, USDA Forest Service, Missoula, Montana.

The actual maximum heights reached by the smoke columns were measured by an instrumented aircraft. Fuel quantity was measured before and after burning, and fuel moistures were sampled at fire time. Standard radiosonde ascents were performed immediately prior to the fires. All weather factors necessary for computing Fire Danger Rating System Indexes were measured and recorded on a regular basis. Watercan fire analogs (Beaufait 1966) were used to measure relative intensities between fires. A multiple regression analysis was used to identify variables which were related to ultimate smoke column heights. After some initial data reduction, the following variables were subjected to regression analysis:

Y(1) = column height (ft above m.s.l.)
Y(2) = column height (ft above terrain)
X(1) = mixing depth (ft above m.s.l.)
X(2) = average upper duff moisture content (percent)
X(3) = windspeed at fire time (20 ft above ground, mi/h) (5-min average)
X(4) = watercan weight loss (g)
X(5) = National Fire-Danger Rating Buildup Index
X(8) = 1/X(2)
X(12) = potential heat yield of fuels in X(16) (Btu)
X(13) = reaction intensity (I_R)
X(14) = rate of spread (ROS)
X(15) = weight of fuels; 0-1 cm diameter + 1-10 cm diameter + needles (g/m^2)
X(16) = weight of fuels; 0-1 cm diameter + needles (g/m^2)
X(17) = average fine fuel moisture; 0-1 cm + needles (percent)
X(18) = 1/X(17)
X(19) = potential heat yield of fuels in X(15) (Btu)
X(20) = mixing depth (ft above terrain)

A computer screen of all possible equations involving the above variables was performed along with machine plots of each independent variable against each dependent variable. The REX-Fortran 4 system for combinatorial screening of multivariate regressions as described by Grosenbaugh (1967) was used in the screening process. This initial attempt revealed that a linear function of X(1), X(12), X(16), and X(17) accounts for 63.2 percent of the variation experienced in Y(1). The computer plots of the variables indicated that variables X(3), X(5), and X(18) vary as some function of the column height above mean sea level. A computer program was employed to find the single-term equations of best fit for each of these three independent variables, versus column height. The resulting functions were added to the independent variable list. They are X(6), X(7), X(9), and X(11) below, and were selected as a convenience in curve fitting, not because of any physical inference. The independent variables found to be nonsignificant in the initial analysis were eliminated.

The final screen of all possible equations examined combinations of the following variables:

Y(1) = column height (ft above m.s.l.)
Y(2) = column height (ft above terrain)
X(1) = mixing depth (ft above m.s.l.)
X(2) = average upper duff moisture content (percent)
X(3) = windspeed at fire time (2- ft above ground, mi/h)
X(4) = watercan weight loss (g)
X(5) = National Fire-Danger Rating Buildup Index
X(6) = square root of X(5)
X(7) = Log_{10} X(5)
X(8) = 1/X(2)
X(9) = square root of X(3)
X(10) = square root of the potential heat yield of the (0-1 cm + needles) fuels
X(11) = square root of X(8)

RESULTS OF THE ANALYSIS OF MILLER CREEK DATA

The six-variable regression equation with the smallest residual mean square had these six variables:

X(1), X(2), X(3), X(4), X(9), X(11)

where

X(1) = mixing depth (ft above m.s.l.)
X(2) = upper duff moisture content (percent)
X(3) = windspeed (20 ft above ground, mi/h)
X(4) = watercan weight loss (g)
X(9) = square root of X(3)
X(11) = square root of 1/X(2)

The R^2 (coefficient of multiple determination) for this regression is 0.80. That is, 80 percent of the variation in the column height is explained by the regression.

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	6	84,308,688	14,051,448	9.958**
Error	15	21,165,840	1,411,056	
Total	21	105,474,520		

Since tabular $F_{0.01}$ with 6 and 15 degrees of freedom is 3.94, $F_{6/15\ df} = 9.958$ is significant at the 0.01 level. Standard error of the estimation = 1,188 ft.

A "t" test of the regression coefficients to determine if the coefficients are significantly different than 0.0 yielded the following results:

Coefficient	*"t"*	*Level of significance*
b(1)	1.789	0.10
b(2)	1.557	.20
b(3)	3.66	.01
b(4)	2.385	.02
b(9)	3.741	.01
b(11)	1.224	.30

From this test one must conclude that the ultimate column height and fire intensity (watercan weight loss) are closely related. By the same token, the mixing depth is only loosely related to the column height.

As a further verification of this conclusion, a regression analysis was performed using only fuel and weather variables. One simple equation resulting from the analysis is:

$$Y = f \quad X(1),\ X(3),\ X(7),\ X(9)$$

where:

$X(1)$ = mixing depth (ft above m.s.l.)
$X(3)$ = 5 minute average windspeed, 20 ft (mi/h)
$X(7)$ = Log_{10} (BUI)
$X(9)$ = square root $X(3)$

The actual regression equation is:

$$Y(1) = -5{,}578.3 + 0.0381\ X(1) - 2{,}183.6\ X(3) + 3{,}683.9\ X(7) + 10{,}634.0\ X(9)$$

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	4	79,334,496	19,833,624	12.899**
Error	17	26,140,032	1,537,649	
Total	21	105,474,528		

Since tabular F distribution with d = 0.01, and df = 4 and 17 is 4.34, the regression is significant at the 0.01 level. The standard error of the estimation is 1,240.0 ft. The coefficient of multiple determination is:

$$R^2 = \frac{\text{Regression SS}}{\text{Total SS}} = \frac{79{,}334{,}496}{105{,}474{,}540} = 0.752$$

A "t" test of the regression coefficients yields the following:

Coefficient	*"t"*	*Level of significance (df = 17)*
b(1)	1.759	0.10
b(3)	4.670	.001
b(7)	2.558	.05
b(9)	5.020	.001

This test indicates that only b(1) is of questionable significance. There exists a probability of 10 percent that assuming b(1) is not zero would lead to an erroneous association.

Again those variables influencing fire intensity (wind and fuel dryness) are notably more closely related to the ultimate level of smoke rise than was the mixing depth.

CONCLUSIONS

Atmospheric stability, expressed as mixing depth, is shown to be eminently inadequate for describing the ultimate level of smoke rise from high-intensity, 10-acre broadcast slash fires. The level to which smoke rose on 22 of these fires is shown conclusively to be closely related to the character of the fire, namely fire intensity.

Management Interpretation

Land managers burning slash must prepare environmental impact statements and burn to maintain a quality air resource. Many fire managers believe that low-level atmospheric stability, expressed as mixing depth, is an absolute prediction of how high the smoke will go. The findings expressed in this paper show that in high-intensity broadcast slash fires of 10-acre, size, the characteristics of the fire are overwhelmingly important to the elevation of the smoke.

Although low-intensity fires do tend to produce a column height more nearly equal to the mixing depth, some of the intense fires used in this study produced smoke columns 8,000 ft higher than the mixing depth. This is significant to the land manager who must accomplish a certain amount of burning in a limited amount of time while assuring good smoke dispersal. A brisk, hot fire can overcome a shallow stable layer of air and produce a high smoke column; however, it would be irresponsible to set off a wet, cool, slow-moving fire under similar lapse rates.

Ideal conditions for good elevation of the smoke are a high mixing depth and fuels dry enough to produce an intense fire.

Nevertheless, the results of this study indicate that a manager should not necessarily refrain from burning solely because the atmosphere is more stable than desirable, if he conducts intense fires. Intense fires are compatible with other management objectives such as seedbed preparation and hazard reduction as well.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)